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Review

Heat-Mitigation Strategies to Improve Pedestrian Thermal Comfort in Urban Environments: A Review

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Abstract: Thermal comfort is one of the main factors affecting pedestrian health, and improving thermal comfort enhances walkability. In this paper, the impact of various strategies on thermal-comfort improvement for pedestrians is thoroughly evaluated and compared. Review studies cover both fieldwork and simulation results. These strategies consist of shading (trees, buildings), the orientation and geometry of urban forms, vegetation, solar-reflective materials, and water bodies, which were investigated as the most effective ways to improve outdoor thermal comfort. Results showed that the most important climatic factors affecting outdoor thermal comfort are mean radiant temperature, wind speed, and wind direction in a microclimate. The best heat-mitigation strategy for improving thermal comfort was found to be vegetation and specifically trees because of their shading effect. The effect of height-to-width (H/W) ratio in canyons is another important factor. By increasing H/W ratio, the thermal-comfort level also increases. Deploying highly reflective materials in urban canyons is not recommended, as several studies showed that they could reflect solar radiation onto pedestrians. Results also showed that, in order to achieve a satisfactory level of thermal comfort, physiological and psychological factors should be considered together.

Keywords: thermal comfort; outdoor environments; pedestrians; heat mitigation; microclimates

1. Introduction

A significant part of the global rural population has migrated to cities, and urban populations are rapidly growing [1]. In 2003, the United Nations predicted that about 61% of the global population will live in cities by 2030 [2]; this has already happened in many developed and developing countries. Population growth in cities is aligned with the increase in construction and urban densification [3], which ultimately result in thermal discomfort in cities.

The outdoor environment is of high importance in cities, since it includes various pedestrian activities. The comfort level of pedestrians in such spaces has direct impact on the presence of people in outdoor environments [4–7].

Thermal comfort is one of the most important factors affecting the quality of outdoor environments for pedestrians [8]. Better thermal comfort leads to the presence of more people in open spaces [9]. Urban open spaces such as town squares, green spaces, or parks bring different environmental, social, and economic benefits [8]. Thermal discomfort, on the other hand, reduces the power of thinking and concentration of pedestrians [10]. Therefore, thermal comfort in hot and cold seasons is considered a necessity for users of outdoor environments. Thermal comfort in open spaces is crucial and must be thoroughly considered when designing an open space since it is affected by a wide range of variables [11].

1.1. Research Method

These steps were followed to prepare the review paper:

(1) Data collection: research began with peer-reviewed papers published in English within the ScienceDirect, Scopus, Wiley, and Springer databases.
(2) Postprocessing of collected data: papers were categorised on the basis of their general topics, forming the four main sections of the paper.
(3) Classification: papers in each section (each heat-mitigation strategy) were studied, and the findings of each study were recorded.
(4) Writing up the body: each section was comprehensively written, including studies from different climates for each chapter (heat-mitigation strategy).
(5) Conclusion and final review: the conclusion was written considering that it should respond to the reviewed sources in terms of the widely used research methods, used software, studied climates, etc.

Regarding the structure of this paper, the chronology of outdoor thermal-comfort studies is first introduced. Our research keywords were "outdoor thermal comfort", "heat-mitigation strategies", ″thermal-comfort indices", and ″urban-canyon geometries". Studies were covered that had been published since the 1970s. Second, different research methods used in outdoor studies are presented, and the frequency of using different methods is shown with a graph. Third, the different simulation software used in modelling outdoor comfort studies is presented. Different indices used for measuring outdoor thermal comfort are also addressed. Lastly, different heat-mitigation strategies within urban environments are reviewed. The main contribution (and novelty) of this paper to the current body of the literature is that, on the basis of different research methods and indices of thermal-comfort studies, heat-mitigation strategies are comprehensively presented. In contrast to previous review studies that focused on nature-based solutions, canyon geometries, or green/reflective materials, all these strategies are reviewed here, considering their research method(s), geography, comfort index, and effectiveness in improving pedestrian thermal comfort. Results of this review paper help to better understand different outdoor-thermal-comfort approaches that are practised in different climates and countries, and the selection of suitable strategies in practice (see Figure 1).

Due to the complexity of outdoor environments (compared to indoor environments), thermal comfort in open spaces is less studied. The beginning of such studies dates back to the last few decades of the 20th century. Figure 2 shows the annual record of publications in this topic. There were few studies in the 20th century regarding outdoor thermal comfort. In Figure 3, the most common research methods on thermal comfort are shown with fieldwork, simulations, and their combination. However, in recent years, the development of simulation software has led to a rapid growth in the number of simulation-based studies in combination with fieldwork.

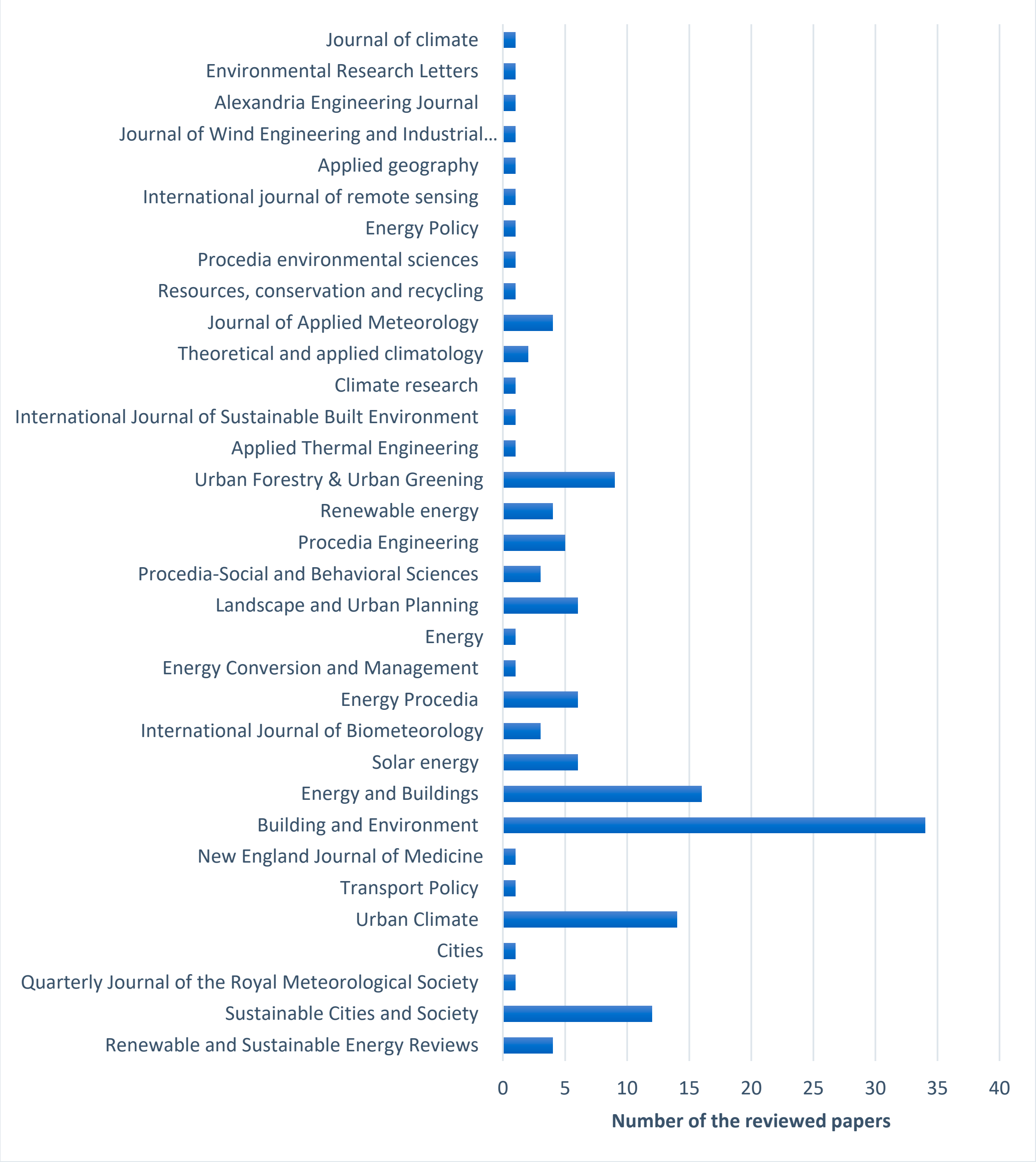

Figure 1. Journal specification and frequency of sources used in this review article.

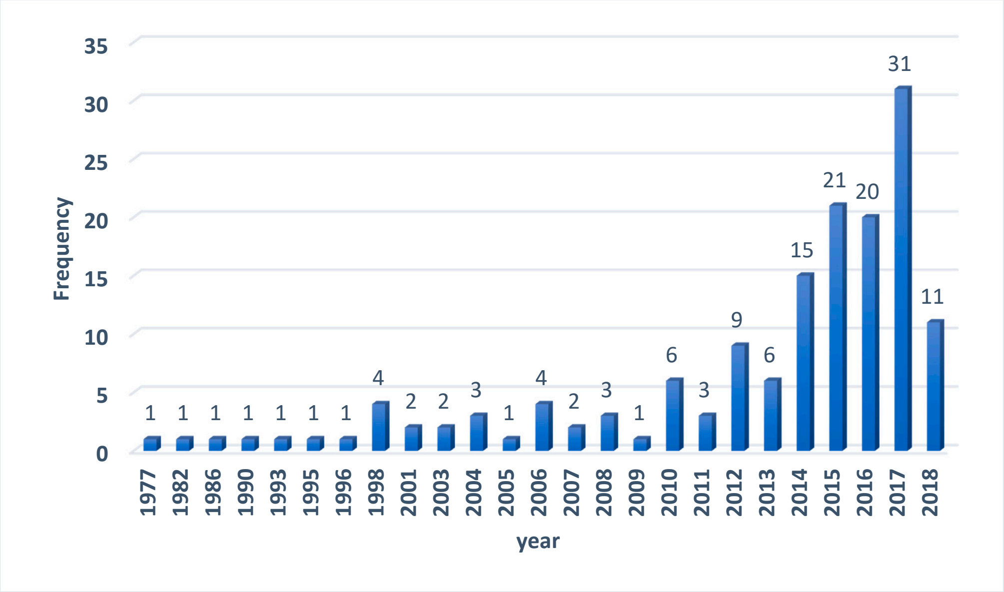

Figure 2. Year-dispersion graph of related studies.

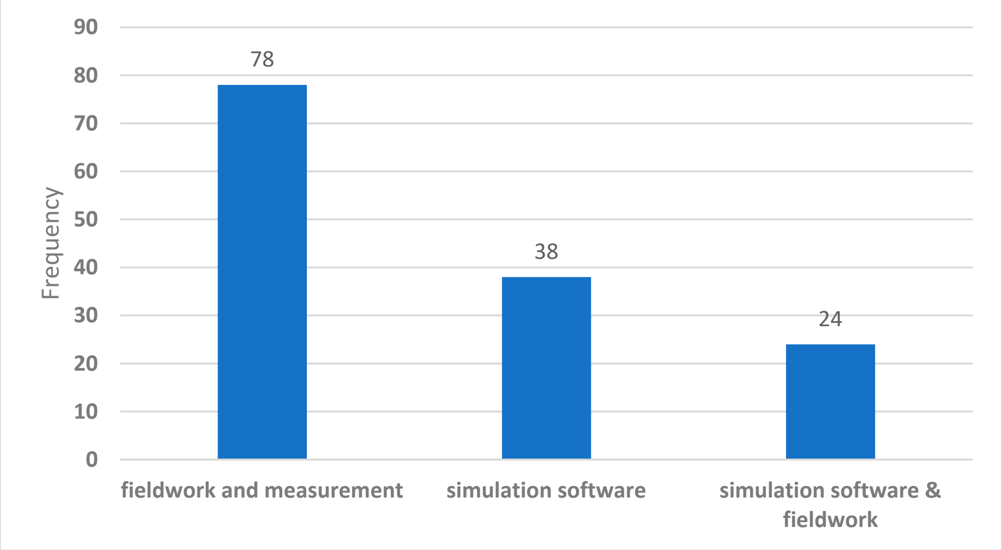

Figure 3. Research methodology regarding outdoor thermal comfort.

Regarding the novelty of this paper:

(a) Outdoor-thermal-comfort papers published from 1977 onwards are comprehensively examined. Papers from journals with high-impact factors were specifically considered. In total, 153 studies were reviewed.

(b) Most previous studies focused on specific climates. In this paper, various heat-mitigation strategies in different global climates, from Canada to Australia, were reviewed.

(c) Previous papers reviewed either nature-based solutions (green strategies such as living walls) or urban design solutions (e.g., canyon effects). This study utilises a holistic approach to include all aspects of heat-mitigation strategies for urban designers and planners.

1.2. Background of Outdoor-Thermal-Comfort Studies

In 1971, the first studies were carried out regarding the impact of microclimates on outdoor activities [4]. Using the number of people sitting on shaded and unshaded benches showed that sunny or shady conditions affected people’s willingness to stay or leave. It could be concluded that the physical conditions of a location affect thermal comfort.

In 1982, Fanger [4] suggested and presented the predicted mean vote (PMV), which predicts the average heat response of people on a 7-point scale to assess their thermal comfort. In 1987, Mayer and Hoppe [4] presented the physiologically equivalent temperature (PET) for the assessment of thermal comfort in external environments (see Appendix A for PET ranges).

In 2001, one of the very first studies in the field of outdoor thermal comfort was based on people's behaviour. In this study, Nikolopoulou et al. [12] examined the thermal-comfort conditions within open spaces in Cambridge, United Kingdom. They evaluated the sensory perception of every individual on a scale of 1–5. In this study, only 35% of the participants experienced the desired thermal comfort. It was concluded that a physiological approach for the assessment of outdoor thermal conditions is not sufficient, while the health history and expectations of individuals play a significant role.

In 2004, Thorsson et al. [13] investigated the impact of biological conditions on people's behavioural patterns via 280 questionnaires in a park as a resting place in Gothenburg, Sweden. A comparison of the results showed that thermal expectations had significant impact on the mental assessment of individuals regarding the thermal comfort of their surrounding environment.

In 2010, Lin et al. [14] studied the effect of shadowing on thermal comfort in outdoor environments. They conducted 12 field tests at a university campus in central Taiwan with a tropical climate. They evaluated the thermal conditions of the campus using RayMan software to calculate the PET index. It was concluded that in the very hot summers and mild winters of Taiwan, a thermally comfortable microclimate is possible with the shading impact of trees and buildings.

In 2012, Makaremi et al. [11] used PET to assess the outdoor environment of the Malaysian Putra University campus (tropical climate). They found out that shaded places have a longer period of acceptable temperature range. Furthermore, while studying the temperature tolerance of native and non-native students, they found out that native students could tolerate a higher temperature rate in comparison with non-native students due to their thermal adaptation to Malaysia's climate.

Huang et al. [15] investigated temperature differences within a university in northwestern China considering different scenarios with increased green spaces, water elements, and highly reflective surfaces using ENVI-met. It was concluded that increasing green spaces led to a maximal reduction of temperature by 0.3 °C, as well as a decrease in maximal mean radiant temperature by 32.1 °C.

Taleghani [16] concluded that, among different climatic factors, mean radiant temperature has the greatest impact on thermal comfort in outdoor environments. He also found that using vegetation in urban environments is better than using highly reflective surfaces.

Salata et al. [17] measured air temperature within the campus of Sapienza University of Rome, Italy (Mediterranean climate). They found that concrete pavements had higher albedo and lower thermal capacity than those of asphalt, and this could improve thermal conditions.

Studies in the past few decades were mainly based on measurements, field observations, and questionnaires. These studies further examined the causes and effects that affect human thermal comfort in outdoor environments. In recent decades, simulation tools for outdoor environments have revolutionised the development of these studies. These simulation programmes evaluate the outdoor thermal environment using various indices. Figures 4 and 5 show the extent of using the software and indices used in the reviewed studies in this paper.

On the basis of Figures 4 and 5, it is evident that ENVI-met and RayMan, respectively, are the most popular simulation tools. In addition, PET and PMV indices are widely used to evaluate thermal environments in various studies.

In many studies conducted in recent years, outdoor-thermal-comfort assessment was performed on the basis of PET index. In these studies, there is a table defining the relationship between thermal perception and PET index or acceptable temperature in the climate. Table 1 shows the neutral or acceptable temperature in a number of studied climates, and the acceptable temperature range or neutral PET for different climates in order to obtain a desirable thermal condition.

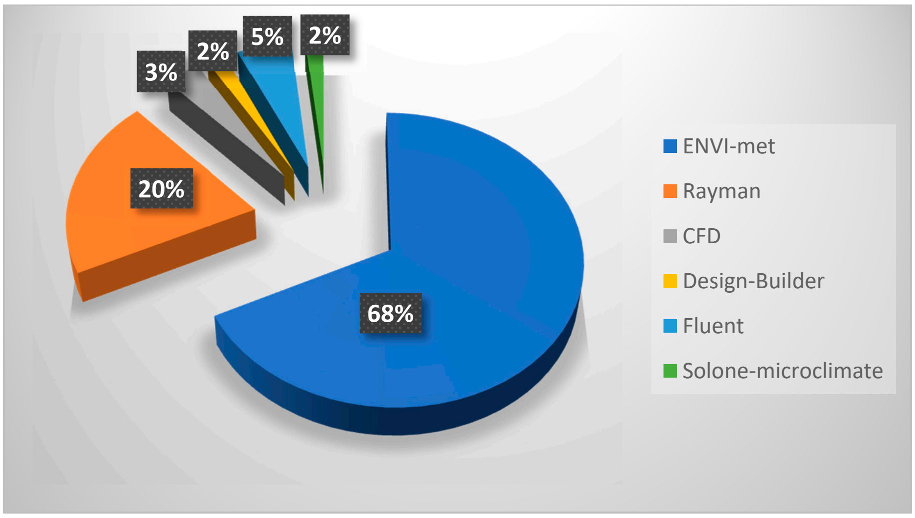

Figure 4. Usage percentage of various simulation tools regarding outdoor thermal comfort.

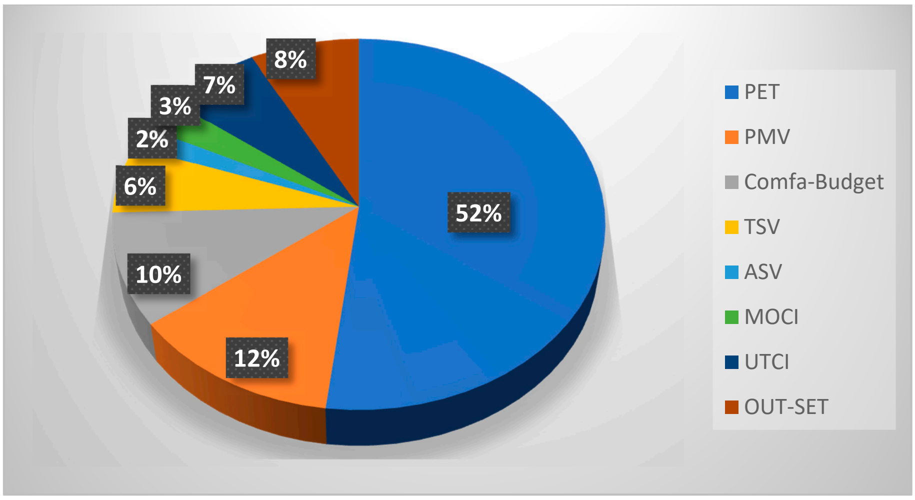

Figure 5. Usage percentage of various indices to assess outdoor-thermal-comfort conditions.

Table 1. Neutral physiologically equivalent temperature (PET; acceptable temperatures) in different climates.

Geographical Region	Climate	Temperature Range (°C)	References
Malaysia	Temperate	18–23	[11]
Malaysia	Subtropical	26–30	[11]
Isfahan, Iran	Hot and dry	23.06–29.73	[18]
Central and western Europe	Temperate	18–23	[19]
Taiwan	Tropical	26–30	[19]
Crete, Greece	Mediterranean	20–25	[20]
Athens, Greece	Mediterranean	18–23	[21]
Hong Kong	Hot and humid	28	[22]
Nis, Serbia	Temperate	18–23	[23]
Sao Paulo, Brasilia	Hot and humid	27.2	[24]
Hong Kong	Tropical	25–29	[25]
Sydney, Australia	Subtropical	26.2	[26]
Belo Horizonte, Brasilia	Tropical	19–27	[27]
Belo Horizonte, Brasilia	Tropical	16–30	[28]
Freiburg, Germany	Continental	18–28	[28]
Ibadan, Nigeria	Tropical	23–27	[29]
Dhaka, Bangladesh	Tropical	28.5–32.8	[30]
Singapore	Tropical	26–31.7	[31,32]

Guangzhou, China	Subtropical	28.54–31	[32]

In this review, the impact of some of the most important and influential variables on the thermal comfort of outdoor environments is investigated. Table 2 illustrates and categorises research themes in the field of outdoor thermal comfort.

Table 2. Themes in field of outdoor comfort. Note: H/W, height to width; SVF, sky-view factor.

Subject	Number	References
1- Climatic parameters affecting outdoor comfort	17	[8,10,16,18–20,31,33–42]
2- Effect of shading on outdoor comfort	15	[21–23,34,42–52]
3- Effect of H/W and SVF on outdoor comfort	25	[14,21,24,30,37,38,53–71]
4- Effect of trees (shading and morphology) on outdoor comfort	26	[10,21,24,25,33,35,53,55,57,72–88]
5- Effect of orientation and geometric form of urban canyons on outdoor thermal comfort	12	[24,37,39,63,89–96]
6- Effect of green, blue, and white surfaces on outdoor comfort	12	[15,16,97–106]
7- Effect of vegetation on outdoor comfort	25	[17,48,56,67,102,103,107–125]
8- Effect of ceiling and green walls in urban canyons on outdoor comfort	10	[62,68,82,126–132]
9- Impact of modern materials in urban canyons on outdoor comfort	10	[133–142]
10- Effect of water elements on outdoor comfort	6	[36,143–147]
11- Impact of psychological factors on outdoor thermal comfort	7	[9,12,26,148–153]

Figure 6 shows the type of urban spaces used in the reviewed thermal-comfort studies. Most studies were performed in the field of outdoor thermal comfort in public spaces. The study of urban canyons, university campuses, and urban parks follows. The fewest studies regarding this topic are about historical sites, residential complexes, and urban squares.

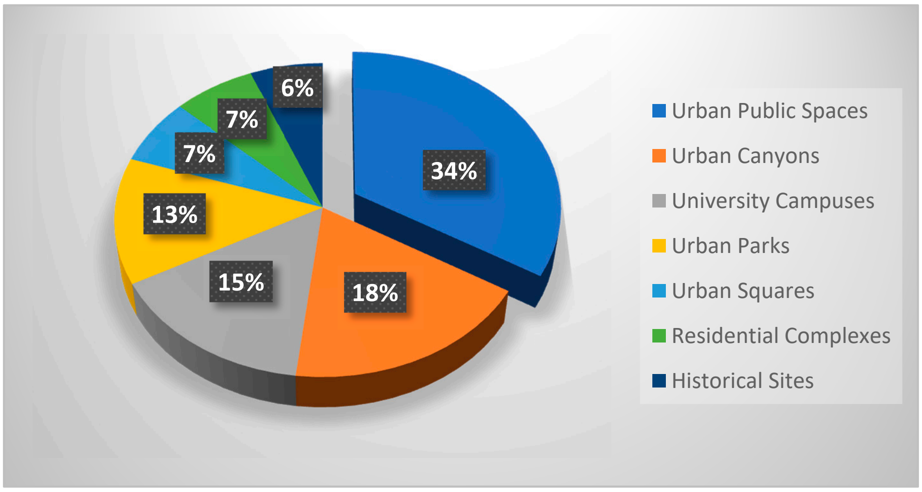

Figure 6. Usage percentage of studies in field of outdoor comfort.

The distribution map of these studies in different climates is shown in Figure 7, showing that these studies focused more on Europe and East Asia.

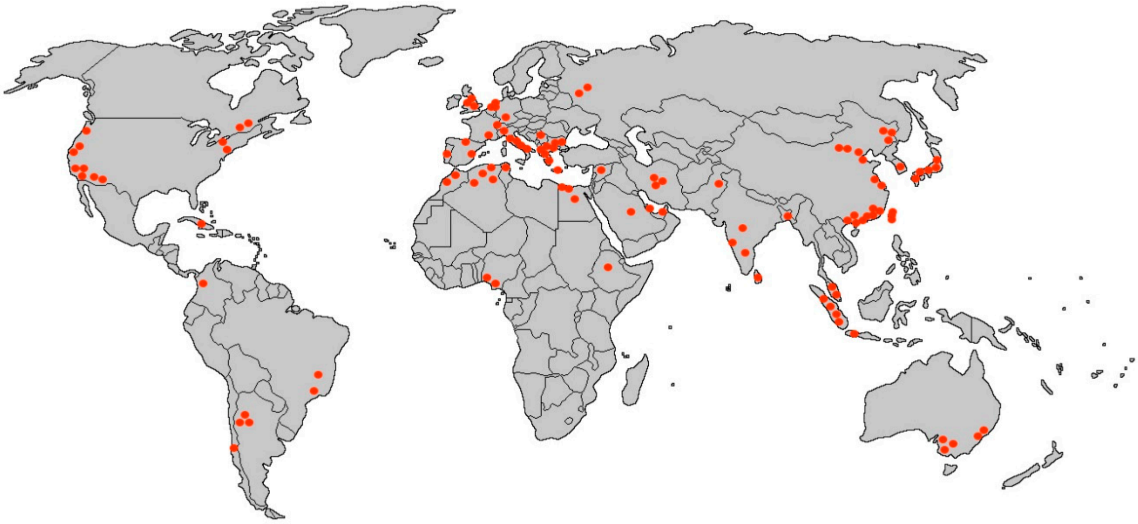

Figure 7. Climate-dispersion map of outdoor-thermal-comfort studies.

2. Climatic Parameters Affecting Thermal Comfort

Climatic parameters that affect thermal comfort are air and mean radiation temperature, relative humidity, and wind speed. Among climatic parameters stated in several studies, mean radiation temperature (mostly derived from solar radiation) is known as the most influential factor affecting thermal comfort in outdoor environments [16,18,31,33–38].

Taleghani et al. [39] researched outdoor external thermal comfort by examining five different urban forms in the Netherlands. In another study on a university campus in Hong Kong, it was also observed that radiation temperature and wind speed play major roles in creating thermal conditions in outdoor environments [19]. Mahmoud [40] also investigated the thermal-comfort level in an urban park in Cairo, Egypt with a hot and dry climate. They found out that the most important factors affecting outdoor thermal comfort are mean radiant temperature and wind speed. In the analysis of outdoor thermal comfort at the Guangzhou Higher-Education Megacentre, Li and Lixiu [41] found that air temperature and mean radiant temperature are the most influential factors on outdoor thermal comfort. In another study, Tsitoura et al. [20] obtained similar results with those of Li and Lixiu while investigating thermal comfort in the island of Crete, Greece.

Yoshida et al. [10] showed that radiant and air temperature are the most important factors with regard to outdoor thermal comfort while examining the effects of tree canopies on the thermal environment of the University of Osaka, Japan. In a study of thermal comfort in Harbin, China, Jin et al. [42] found that, in warm seasons, radiant temperature has the greatest effect on thermal comfort in outdoor environments, followed by wind speed and air temperature.

Chen et al. [8] examined a city square/park during the cold seasons of Shanghai, and considered air temperature and mean radiant temperature as the most important factors regarding outdoor thermal comfort in winter. They also found that people's presence in outdoor environments during winter is directly related to available solar radiation; the longer the sun is available, the longer the amount of time that people spend in outdoor environments.

Reviewing thermal-comfort studies in outdoor environments, it is evident that, in order to obtain thermal comfort, it is important to address strategies such as shading and the use of green–white–blue surfaces while considering the form and geometry of city canyons, and the psychological factors of individuals. In most thermal-comfort studies, the main focus is on only one or two climatic factors and the strategies to improve them. However, the strategies used for other climatic factors may have an adverse effect on other factors. Therefore, comprehensive attention on all climatic factors is recommended.

3. Shading Effect

Controlling solar radiation is the most important factor affecting outdoor thermal comfort, especially in hot seasons [43–45]. Kariminia et al. [34] investigated outdoor thermal comfort within the two urban squares of Naghshe-Jahan and Jolfa in the hot arid climate of Isfahan, Iran. Using field measurements and questionnaires, they found out that Jolfa has more comfortable hours mainly due to the shading effect of its walls.

Hwang et al. [50] explored the effect of urban canopies on thermal comfort in different seasons. By using RayMan software, they showed that, in summer, spring, and autumn, shading is recommended, whereas in winter, there is minimal need for shadowing. Therefore, they proposed deciduous trees.

Ng and Cheng [22] investigated thermal comfort in the hot and humid climate of Hong Kong using field measurements. They concluded that, at a temperature of 29.7 °C, surfaces exposed to direct radiation experienced a surface temperature in the range of 50–60 °C, while this value for shaded surfaces was in the range of 30–34 °C.

Watanabe et al. [51] studied thermal comfort within the campus of the University of Nagoya, Japan in both shaded and unshaded areas. They found that, under solar-radiation intensity of 800 W/m^2, the universal-effective-temperature index was reduced by 18.4 °C by the shading of buildings, and by 16.2 °C by the pergola.

Morakinyo et al. [52], in an experiment on the outdoor thermal conditions of two buildings (one with and one without tree shading) at Akure University in Nigeria (tropical climate), found that the air temperature around the building without tree shading was always higher than that of the building with shading.

Djekic et al. [23] studied the impact of sidewalk materials on raising the local temperature in summer in Nis (Serbia; temperate climate). They showed that temperature differences between the shaded and unshaded surfaces were up to 20 °C.

Most studies on the effect of urban canopy shading on outdoor thermal comfort were conducted in warm seasons. Some canopies reduce the amount of sunlight in winter and increase thermal discomfort. Therefore, the effect of shading on thermal comfort should be examined in both warm and cold seasons.

3.1. H/W and SVF

Shading by buildings is an important strategy for creating thermally comfortable conditions for pedestrians in urban canyons. In addition, a low sky-view factor (SVF) or less openness to the sky in urban canyons caused by tall buildings and trees improves thermal comfort during warm seasons [14,53–56]. In several studies, various proportions of building height to street width (H/W) were investigated with respect to thermal comfort [53–57–60].

Yang et al. [61] investigated thermal comfort in high-rise-building areas of Singapore using ENVI-met. They concluded that, in a warm and humid climate, a height-to-width ratio of 3 and above can provide outdoor thermal comfort for pedestrians.

Jamei and Rajagopalan [62] used ENVI-met and examined a microclimate in Melbourne, Australia. They concluded that, by increasing the height of buildings, temperature drops by 1–4 °C.

Achour-Younsi and Kharrat [63] studied the H/W ratio of three urban streets in Tunisia with subtropical Mediterranean climates using ENVI-met. They found that the universal-thermal-climate-index (UTCI) difference between H/W of 0.25 and 4 was 8.48 °C. Furthermore, as H/W increases, thermal comfort improves.

Johansson [64] investigated the effect of urban geometry on outdoor comfort by comparing a shallow street (low H/W) with a deep street (high H/W) in Fez (Morocco; hot and dry climate). It was concluded that, during warm summer days, comfortable hours at the deep streets were more than those in the shallow one.

Kariminia et al. [38], using ENVI-met, looked at the role of geometry on the thermal comfort of visitors from a historical site in Isfahan, Iran (hot and dry climate). Their results suggested that, by increasing the H/W ratio from 0.1 to 0.3 in a historic square, PET was decreased by 1.6 °C. This decreased the discomfort period by 3 h.

Rodríguez-Algeciras et al. [65] studied 4 different H/W ratios within the central courtyards at Camagüey in Cuba (warm and humid climate). They showed that a H/W ratio of 3 in comparison with 0.5 reduced mean radiant temperature by up to 20 °C.

It was concluded that increasing H/W and the consequent shading effect improve thermal conditions in urban canyons [21,24,30,37,66–71]. Many studies were conducted in order to increase thermal comfort by increasing H/W during warm seasons. However, increasing the H/W does not improve thermal comfort in winter, so this solution is not recommended in cold climates. Further studies are needed to determine how this solution could work in different climates.

3.2. Trees

Trees are considered as a strategy to enhance thermal comfort in outdoor environments for different reasons, including their shading effect [72–76]. Several studies were used to reduce air temperature and radiant temperature, control wind speed and moisture, and generally improve thermal-comfort conditions [33,53,77–79]. In some studies, trees were identified as the most effective strategy for thermal comfort in outdoor environments among various other approaches [21,57,80–82].

Ruiz et al. [57] investigated 12 different urban streets in Mendoza, Argentina and concluded that there was a 60% improvement in thermal comfort in streets with trees compared to bare ones.

Johansson et al. [24] studied thermal conditions in 6 different urban environments (). The study was performed in the warm and humid climate of Sao Paulo, Brazil using the BRAMS and ENVI-met simulation packages. Results showed that the vegetated area had the highest thermal comfort.

Stocco et al. [55] studied 3 different areas in Mendoza, Argentina and found that areas with the highest tree density had the lowest air temperature.

Tree-growth scenarios are being investigated using tree forecast prediction models in a span of 30 years ranging from 2002 to 2032 in Milan, Italy. It was observed that, with the growth of trees and the increase in their umbrellas, a decrease in radiant temperature, and thermal-comfort improvement were estimated [83].

Tree Morphology

Trees are of great importance in outdoor environments due to their effective shading effect and for improving thermal-comfort conditions in urban streets. In some studies, a tree species with its specific morphology and climatic conditions in the study area was discussed.

Kong et al. [84] looked at the impact of tree types on outdoor thermal environments in Hong Kong. They concluded that trees with larger crowns, such as *Macaranga tanarius*, *Ficus microcarpa*, and *Acacia confusa* are more recommended over those with small crowns such as *Melaleuca*, *Leucadendron*, and *Livistona chinensis.*

Hanafi and Alkama [85] investigated the role of vegetation in outdoor environments in the warm and dry climate of Biskra, Algeria. They observed that *Ficus* trees (as a group of large crowns) were the most suitable.

Correa et al. [35] studied 3 different streets with widths of 16, 20, and 30 m in Mendoza, Argentina. They concluded that *Platanus* × *acerifolia* had the best performance among 3 common tree species in that area.

Yoshida [10], examining the effect of tree shadows on the thermal environment within the University of Osaka, Japan, concluded that trees with smaller leaves perform better than those with larger leaves in terms of thermal comfort.

In another study in Hong Kong (tropical climate), Morakinyo et al. [25] examined the influence of 8 tree species on outdoor thermal environments and concluded that leaf-area index is the most important physiological factor of trees. They recommended trees with narrower crown width, less density, and greater trunk height in high-density canyons.

Zhao et al. [86] analysed the biological properties of five different tree species in Harbin, China. They found that the species of *Populus × berolinensis*, *Populus alba,* and *Acer saccharum* had greater impact on climatic and thermal comfort during summer, with maximal PET reductions of 4.7 to 15.9 °C, respectively. It was also concluded that tree umbrella width and density were the most important biological factors in creating thermal comfort.

In another study, the impact of different tree-planting scenarios on the thermal comfort of outdoor environments was examined in Phoenix, Arizona, United States (hot and dry climate). The most appropriate scenario was the planting of trees with a distance of two trees, followed by a cluster model without overlapping the canopy [87].

Morakinyo et al. [88] studied the influence of common tree species in Hong Kong regarding thermal comfort of outdoor environments. They found that dense and medium-sized trees are suitable for shallow streets, while low-density trees were suitable for deep canyons. They also found that the most important features of trees for improving the thermal comfort of outdoor environments were leaf-area index, trunk height, tree height, and crown diameter.

Despite the important role of trees in shading and improving thermal comfort, few studies considered them in the context of various climates. This can help urban planners include the most suitable types of trees in terms of thermal comfort before designing urban canyons.

3.3. Urban-Canyon Orientation

The orientation of urban canyons with regard to the direction of sunlight and the prevailing wind in each climate is an important factor for creating the desired thermal comfort in outdoor environments [89].

Targhi and Van Dessel [90] studied different points in north–south and east–west streets by using ENVI-met and RayMan on 2 July 2014 (the hottest day of the year) in Winchester, USA. They found that the north–south street was more comfortable due to the solar radiation.

Achour-Younsi and Kharrat [63] investigated the H/W of three streets in Tunis (subtropical Mediterranean climate). The obtained results showed that, in all streets with a fixed H/W ratio, the best orientation was north–south, while the worst orientation was east–west.

Johansson et al. [24] found that, in the warm and humid climate of Brazil’s Sao Paulo, streets with northwest–southeast and southwest–northeast orientations performed better in terms of thermal conditions in comparison with north–south and east–west orientations.

In another study, four different orientation scenarios were simulated at a university campus in Dubai (hot and dry climate). Using ENVI-met(Essen, Germany), it was found out that 2 scenarios with low-rise buildings that were facing the wind flow enhanced overall thermal comfort [91].

Ali-Toudert and Mayer [37] simulated a comparison between urban canyons with a similar H/W and different orientations using ENVI-met in Ghardaia, Algeria (hot and dry climate). They found that northeast–southwest and northwest–southeast streets thermally perform better than those with north–south and east–west orientations. In Concepción, Chile (mild climate), diagonal urban canyons were found to have the best performance in terms of both physical and psychological thermal comfort [92].

Cao et al. [93] investigated the effect of street orientation on local thermal comfort in Guangzhou, China using Fluent. Their final results showed that having the same wind flow and street direction increases average wind speed while decreasing mean radiant temperature.

3.4. Geometrical Forms

Different urban forms can create various microclimatological conditions in regard to the pedestrian comfort in cities.

Taleghani et al. [39] studied five different urban geometrical forms (singular north–south and east–west, linear north–south and east–west, and central courtyard) in the Netherlands. The central courtyards (that received low solar radiation) were the best form, while singular (with a high amount of received direct sunlight) were considered to be the worst. In another study, conducted by

Taleghani et al. [94] in the Netherlands, the central courtyard was considered to be the best and the singular form the worst for heating and cooling energy consumption.

Xi et al. [95] researched various geometric forms at the University of Guangzhou (subtropical climate) and concluded that the pilot form had the best thermal performance, and could reduce the air temperature during the summer by 2 to 3 °C.

Field measurements of the building materials, pavements, and urban geometry of 4 residential neighbourhoods in Rome during 2015 and 2016 showed that suburban areas were more thermally comfortable in comparison with those downtown [96]. It was concluded that the denser urban geometry in the Mediterranean region causes thermal dissatisfaction in outdoor environments [96]. However, this conclusion cannot be considered valid for other climates, especially hot climates where shading can improve thermal comfort.

4. Green, Blue, and White Surfaces

Among different available strategies to improve thermal comfort in outdoor environments, it is important to consider surfaces covering urban streets such as pavements, building facades, and roofs. Several studies addressed the role of green surfaces (vegetation), water surfaces (blue elements), and white surfaces (high-reflection surfaces).

Taleghani [16] studied the role of vegetation and highly reflective materials as the most common solutions for improving thermal comfort in urban canyons. It was concluded that vegetation and reflective surfaces significantly decrease ambient air temperature. However, high albedo surfaces reflect the sun’s rays and cause thermal discomfort, which is why the use of vegetation is recommended more.

Martins et al. [97] used ENVI-met to simulate thermal-comfort conditions within a new urban area in Toulouse, France. It was concluded that increasing vegetation and water surfaces led to a 7 and 2 °C reduction in PET, respectively.

Morille and Musy [98] assessed three strategies of green, water, and reflective surfaces using the SOLENE-Microclimate simulation tool in Lyon, France. They found that green surfaces had the best thermal performance. However, highly reflective materials reflected solar radiation back to the pedestrians, and poorer thermal performance was observed in comparison with that of green and water surfaces.

Huang et al. [15] studied the impact of increasing green, water, and white surfaces at a university campus in northwest China. Results showed that green surfaces decreased air temperature and mean radiant temperature by 0.3 and 32.1 °C, respectively. However, the reduction in air temperature for white surfaces was 1.1 °C, while mean radiant temperature was increased by 5.4 °C. Water surfaces had minimal effect on reducing air temperature and mean radiant temperature.

The current climate in Athens, Greece (Mediterranean climate) was compared with scenarios where green, water, and white surfaces were added to the land cover [99]. It was concluded that the second scenario (more water bodies) provided better improvement for outdoor thermal comfort.

In another study, green, water, and reflective surfaces were analysed as the main strategies for either preventing or decreasing the effects of heat islands in a university campus in Hong Kong, and the authors concluded that green and water surfaces significantly reduced heat, while reflective surfaces had an adverse effect [100].

Taleghani and Berardi studied a crowded area during the hottest days of 2015 in Toronto, Canada. The increase in albedo level from 0.1 to 0.3 and 0.5 resulted in a decrease in air temperature by 0.5 and 1 °C, respectively. However, this increase in albedo led to an increase in the reflection of sun rays, and subsequently an increase in the thermal discomfort of pedestrians [101].

Numerous studies indicated that highly reflective surfaces, despite reducing air temperature, have an adverse effect in terms of a greater reflection of sun rays in urban canyons, which ultimately increases the thermal discomfort of pedestrians [101–103]. In general, it is recommended to use surfaces with high reflectivity on the roofs of buildings in order to reduce the energy consumption of the buildings [104–106]. However, the use of such materials in horizontal and vertical surfaces within the urban canyons is not recommended.

4.1. Vegetation

Using vegetation in urban areas such as parks improves overall thermal conditions by decreasing air temperature and mean radiant temperature, and increasing the humidity of the surrounding environment [107–114].

In several studies, the role of vegetation in various urban areas was considered, and the need to use vegetation to enhance thermal comfort was proven [17,48,56,67,103,115–120].

Radhi et al. [121] studied the effect of artificial islands in Bahrain on climatic parameters using computational-fluid-dynamics (CFD) analysis. It was concluded that the mean radiant temperature difference between a vegetated area and concrete surfaces was up to 5 °C.

Barakat et al. [122] assessed 3 different microclimates by using ENVI-met in Alexandria, Egypt (hot and dry climate). They suggested that thermal conditions can be improved by reducing the pavement areas, and increasing greenery surfaces, water bodies, and the number of trees. It is well documented that these changes reduce air temperature and average radiation temperature while increasing humidity.

Georgi and Dimitriou [123] analysed the effect of vegetation on improving thermal conditions of Chania in the island of Crete (Mediterranean climate). In an area of 100 m^2, they assessed 3 different vegetation strategies, namely, the planting of 8 trees, using 4 cooling fans, and implementing a cladding canopy. It was concluded that tree planting was financially the best strategy for improving thermal conditions.

Jeong et al. [124] studied and compared the satisfaction degree of people in a forest–urban district in the central area of Seoul. They found that 79.3% of the people in the forest–urban area experienced a comfortable situation, while this value within the central region of the city was 31.1%.

Klemm et al. [125] evaluated 9 streets with a similar geometry in Utrecht, aiming to study the physical and psychological impacts of green spaces on thermal comfort. Results showed that mean radiant temperature in streets with trees was 39% lower than the bare streets.

In a study performed with ENVI-met on the thermal environment of a historic site in Rome, researchers concluded that vegetation improved overall thermal conditions while decreasing the PMV index by 1.5 °C at the middle of a hot summer day [102].

4.2. Green Roof and Wall

Roofs account for about 20%–25% of urban surfaces [126]. Green roofs and walls are two examples of adding vegetation to urban canyons. In a study on Melbourne's urban design with the use of vegetation, it was found that green roofs did not improve the PET index for pedestrians [62].

Perini and Magliocco [68] analysed the cooling impact of green roofs and surfaces on the ground level in the Mediterranean climate of three Italian cities: Genoa, Rome, and Milan. They concluded that green surfaces on the ground performed more efficiently than green roofs did. This was because they reduce air temperature and mean radiant temperature (and consequently PMV) at the height of 1.6 m (pedestrian level). However, green roofs were effective in reducing the cooling load of the buildings.

Taleghani et al. [127] assessed two central courtyards at Portland State University (Portland OR, USA) during summer 2013. One wall was built using red bricks, while the other was a vegetated green wall. They continuously measured thermal conditions within the centre of the two yards bounded by both walls and found that air temperature in the centre of the yard with the green walls at 16:30 was 4.7 °C lower than that of the bare courtyard.

Alexandri and Jones [128] found that green roofs and walls in hot and dry climates had the greatest impact on the improvement of thermal comfort in 9 different cities. This conclusion regarding green walls can be extended to all climates. They also stated that green walls have a greater effect than that of green roofs on reducing air temperature in urban canyons.

Zhang et al. [82] studied the thermal impact of three strategies, namely, green roofs, green facades, and cool roofs in a school in Tianjin, China. They concluded that green facades had the least effect on improving the thermal environment.

Morakinyo et al. [129] examined the thermal benefits of green facades in Hong Kong. They found that, by greening 30–50% of the facades within the city, up to 1 °C air temperature could be reduced in Hong Kong. This situation led to the improvement in thermal conditions by at least one unit.

In general, it can be concluded that green roofs reduce the energy consumption in buildings [130–132]. However, they have little impact on outdoor thermal comfort, especially on the pedestrian level [62,68,128]. On the other hand, green walls can be effective in improving the overall thermal comfort of urban canyons [82,127,129].

4.3. Highly Reflective Materials

Reflective (white) and cold surfaces in urban canyons (especially in dense areas) can reflect the solar radiation, allow for heat to flow back to the atmosphere, and mitigate urban heat islands [133–138].

Castaldo et al. [139] used two types of cold-red and cold-grey concrete composites to study a dense historical site in Rome. They could observe reductions in the Mediterranean outdoor comfort index (MOCI) of 15% and 30% for cold-red and cold-grey surfaces, respectively.

In another study on a historical site in Italy, Rosso et al. [140] used ENVI-met to simulate three concrete types (red, white, and grey), and a specific type of marble in 7 different scenarios. They found that using red concrete on the walls, and grey concrete or marble in horizontal surfaces on the ground level of the urban canyons helped to decrease heat islands while increasing thermal comfort in urban canyons.

Rossi et al. [141] combined thermal, visual, and acoustical comfort using an acoustic white velvet fabric in an effort to study a historical site in Italy.

Lin and Ichinose [142] compared a type of travertine with concrete blocks commonly used on sidewalks in Japan during summer and autumn. The travertine stone was recommended to be replaced by the concrete blocks that have high thermal capacity, high reflectivity, and low thermal conductivity.

4.4. Water Bodies

Water bodies are considered to be a strategy to improve thermal comfort in outdoor environments due to their ability to increase humidity and reduce air temperature in urban areas [143–145].

Xu et al. [146] explored the most suitable place for an exhibition in terms of thermal comfort in Shanghai. They found areas with 10 to 20 m distance from the Huansha artificial water body as the most comfortable places.

A study on thermal comfort around bodies of water in Japan, with the main focus the direction and size of the ponds, suggested that larger ponds prone to prevailing wind can more significantly improve thermal comfort [147].

Mazhar et al. [36] investigated thermal comfort in the outside environments of Lahore (warm and dry climate). They compared Shalimar Gardens with a central courtyard in the Alhambra Arts Council, and concluded that Shalimar Gardens provided a higher level of thermal comfort because of their vegetation and huge water ponds.

5. Psychological Factors Affecting Thermal Comfort

In numerous studies, in addition to microclimatic parameters affecting thermal comfort in the outdoor environment, the effects of psychological factors were investigated [148]. Many studies noted that individuals can consciously or unconsciously adapt to their thermal conditions and achieve thermal comfort [149].

Spagnolo and de Dear [26] rated the thermal comfort of 1018 people in open and semiopen areas in a field study in Sydney, Australia. They found that the number of individuals feeling thermally comfortable in indoor environments was far less than that of those comfortable in outdoor environments. This shows that people in outdoor environments have higher thermal expectations, and they accept a wider range of temperature levels as comfortable.

Nikolopoulou et al. [12] investigated four major touristic sites in Cambridge during spring, summer, and winter. According to their 1431 questionnaires, the thermal-comfort expectations of each individual and their understanding of their thermal environment had significant effects on their thermal perceptions.

In a study in Barranquilla, Colombia (tropical weather), the thermal conditions of pedestrians in five points of the city were investigated. It was determined that people tend to find neutral thermal conditions and cooler environments as ideal thermal conditions. However, in similar studies in tropical climates, it was reported that warm and very hot conditions are desired. This reflects the impact of psychological factors on the perception of individuals of the thermal environment [150].

Lin [151], in a study aimed at discovering the relationship between psychological factors and the use of an urban square in a tropical region, found that, when people decided to stay within the square (sitting in the square etc.), they had high thermal satisfaction, and this satisfaction level dropped when they were forced to cross the square.

In general, thermal comfort relies on both physical and psychological factors. Therefore, people's thermal expectations are an effective factor that determines their level of thermal comfort [9,148,152].

6. Conclusions

The main purpose of this study was to identify parameters affecting the thermal comfort of pedestrians in outdoor environments. More than 150 studies were reviewed. These studies were chosen because they addressed the improvement of outdoor thermal comfort in different climates, used different indices of human thermal comfort, and implemented different research methods (field measurements, computer simulations, or a combination).

The reviewed heat-mitigation strategies were divided into four sections: climatic parameters; shading effects; green, blue and white surfaces; and psychological parameters. Here, the most important lessons learnt from these studies are summarised:

- The conducted studies used different data-collection methods. Field measurements and computer simulations are frequently used in order to analyse thermal environments. The most frequently used strategies to improve pedestrians' thermal comfort include climatic design solutions that are related to the physical properties of urban spaces. These include shading (by buildings and trees), street orientation, and geometrical forms of urban canyons, vegetation, water surfaces, and highly reflective materials. However, many studies confirmed that, in addition to the aforementioned strategies, the psychological factors (perception of people of their thermal environment) and thermal expectations of individuals are also necessary in order to create favourable thermal conditions.
- Among climatic factors affecting outdoor thermal comfort, mean radiant temperature has the greatest effect, followed by wind speed and direction. As a result, strategies that reduce mean radiant temperature (such as shading) are more effective. Results showed that increasing H/W in urban canyons improves outdoor thermal comfort.
- Many studies concluded that deploying different types of vegetation is the best strategy to improve thermal comfort, with an emphasis on trees. By comparing green roofs and walls, it could generally be concluded that green roofs reduce energy consumption for buildings. However, they have little impact on pedestrian thermal comfort. Green walls are more effective than green roofs in improving thermal conditions in urban canyons.
- The use of highly reflective materials in urban canyons tends to increase thermal discomfort due to the reflection of solar radiation (despite the fact that they reduce air temperature). It is not recommended to use such materials in surfaces of urban canyons. Nevertheless, they could be deployed on roofs in order to reduce air temperature in buildings to reduce their overall energy consumption.
- Regarding the orientation and geometries of urban canyons, orientation with respect to the direction of sunlight and the prevailing wind is an important factor for creating favourable

thermal conditions. In addition, the various forms and geometries of urban canyons can affect microclimatic and thermal conditions for pedestrians. There is a direct relationship between area density and thermal comfort. In dense areas, heat is trapped due to less ventilation. Comparing different urban forms, courtyards were found to be the best form in terms of thermal comfort and energy consumption.

7. Recommendations for Future Studies

This paper recommends three topics for further research:

- Considering the significant role of trees in shading and improving outdoor thermal comfort, studies are required on the geometry of trees in each climate. In this way, the most suitable tree species could be used (planted) in order to more efficiently improve outdoor thermal conditions.
- Despite evidence showing that water bodies reduce air temperature and increase humidity, there are not many extensive studies regarding the number, depth, form, and location of water surfaces in urban areas with different climates.
- Using highly reflective surfaces in urban canyons is not recommended, as they reradiate solar radiation back to pedestrians. Further studies can provide scientific solutions in order to regulate and optimally use these materials.

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Appendix A

Table A1. Different ranges of physiologically equivalent temperature (PET) index for different grades of human thermal perceptions [153].

Thermal Perception Grades	PET (°C)
Extreme cold stress	Below 4
Strong cold stress	4.1 to 8
Moderate cold stress	8.1 to 13
Slight cold stress	13.1 to 18
No thermal stress	18.1 to 23
Slight heat stress	23.1 to 29
Moderate heat stress	29.1 to 35
Strong heat stress	35.1 to 41
Extreme heat stress	Above 41

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